New Color-Octet Vector Boson Revisit

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Abstract

Motivated by CDF recent measurements on di-jet invariant mass spectrum where di-jet is associated production with charged leptons (e/μ) and missing energy, we re-examine the previous proposed massive color-octet axial-vector-like boson Z_c. Our simulation showed that the di-jet bump around 120-160 GeV can be induced by Z_c with effective coupling $g_{Z_c q\bar{q}} = 0.2 g_s$ (q represents the quark other than top and g_s is the strong coupling constant). Moreover our numerical investigation indicated that the top quark forward-backward asymmetry A_{FB}^t can be reproduced without distorting shape of differential cross section $d\sigma/dM_{t\bar{t}}$, provided that the Z_c and top quark coupling is appropriately chosen ($g_{Z_c t\bar{t}} \simeq 4.5 g_{Z_c q\bar{q}}$). Our results also showed that the theoretical A_{FB}^t as functions of Δy and $M_{t\bar{t}}$ can be consistent with data within 1σ and 1.8σ respectively.

I. INTRODUCTION

In the previous work [1], part of authors proposed a new massive color-octet vector boson Z_c just above $2m_t$ in order to account for the top quark forward-backward asymmetry A_{FB}^t at Tevatron. Just after [1] posted, a new analysis on A_{FB}^t appeared [2]. The analysis indicated that, in the $t\bar{t}$ rest frame, A_{FB}^t increase with the $t\bar{t}$ rapidity difference Δy, and with the invariant mass $M_{t\bar{t}}$ of the $t\bar{t}$ system. In order to satisfy the measured A_{FB}^t for $M_{t\bar{t}} < 450$ GeV which is consistent with standard model (SM) prediction, m_{Z_c} must be adjusted very carefully to ensure the cancelation of contributions to asymmetric cross section. This feature makes the idea less attractive. However the alternative proposals to account for anomalous A_{FB}^t, for example the t-channel flavor changing Z'/W' contribution and a generic s-channel heavy color octet, will have a risk to distort the shape of $d\sigma/dM_{t\bar{t}}$, especially for the high energy regime. This disadvantage is, in fact, one of our primary motivations to introduce the light color-octet axial-like vector boson.

Recently CDF at Tevatron released their measurements on WW/WZ cross sections via the electron/muon + missing energy + di-jet channel [3–5]. The cross sections are in agreement with the SM prediction. However there seems an unexpected bump in the di-jet spectrum around 120-160 GeV, though the significance (3.2σ [5]) is not significant. The instant investigations showed that the extra vector bosons [6, 7], as well as the new resonance in Technicolor models [8], can account for such bump with appropriate parameters. However the new particles prefer to couple with quarks instead of leptons provided that the severe constraints from other measurements at LEP, Tevatron and even the UA2 experiments. Such feature motivates us to pursue the possibility that the new bump is actually the color-octet axial vector. The obvious reason is that the color-octet does not couple with leptons.

The interaction Lagrangian of Z_c and quarks can be written as

$$\mathscr{L} = i\bar{q}\left(g_V + g_A\gamma_5\right)\gamma_\mu T^a q Z_c^{\mu,a} + h.c. \tag{1}$$

and g_V/g_A are vector- and axial-vector couplings among quarks and Z_c. In order to ensure the successful prediction on $d\sigma/dM_{t\bar{t}}$ in the SM, the extra contribution to the total cross section should be limited. Thus for simplicity we choose $g_V = 0$, same with the choice in

Ref. [1]. This point can be understood from the amplitude squared for the process $q\bar{q} \to t\bar{t}$

$$\sum_{Color,Spin} |M|^2 = \frac{C_A C_F}{2}\{4g_s^4(1+c^2+4m^2)$$

$$+\frac{8g_s^2\hat{s}(\hat{s}-M_G^2)}{(\hat{s}-M_G^2)^2+M_G^2\Gamma_G^2}[g_V^q g_V^t(1+c^2+4m^2)+2g_A^q g_A^t c]+\frac{4\hat{s}^2}{(\hat{s}-M_G^2)^2+M_G^2\Gamma_G^2}\times$$

$$[((g_V^q)^2+(g_A^q)^2)\times((g_V^t)^2(1+c^2+4m^2)+(g_A^t)^2(1+c^2-4m^2))+8g_V^q g_A^q g_V^t g_A^t c]\},$$

$$(2)$$

where $m=m_t/\sqrt{\hat{s}}$, $\beta=\sqrt{1-4m^2}$, $c=\beta\cos\theta$ and $g_V^{q(t)}/g_A^{q(t)}$ are vector- and axial-vector couplings among light quarks (top) and Z_c. Here the terms at rhs represent QCD amplitude squared, interference between QCD and Z_c amplitudes and Z_c amplitude squared respectively.

Why can such light particle Z_c escape the constraints from (1) new resonance search using di-jet invariant mass distributions; (2) quark composite scale limits which are derived from the deviation from the background (mainly from QCD processes) shape of P_T^j or m_{jj}? The reasons are as following.

1. Jet is usually not measured so well as that of charged leptons and the di-jet mass peak can be buried by large mass resolution if the Z_c contribution is less than the huge QCD backgrounds. As the consequence, the Tevatron constraints on new particle less than 200 GeV are quite weak [9]. The UA2 experiment can only effectively constrain such light particle with the coupling strength larger than $\mathcal{O}(g_s)$. The required parameter to account for the new bump is only $0.2g_s$, as shown below, which is permitted by direct searches of past experiments.

2. The shapes and magnitudes of P_T^j and m_{jj} after including the Z_c contributions are not distorted severely, especially at high energy region (much larger than m_{Z_c}). As such the quark composite scale limit is *not* applicable to Z_c.

The paper is organized as following. Section II showed that $W+Z_c$ associated production can account for the di-jet invariant mass distribution observed by CDF [5]. In section III we presented the results for A_{FB}^t and compared with measurements by CDF [2]. Section IV contained our conclusions and discussions.

II.   DI-JET ASSOCIATED PRODUCTION WITH e/μ AND MISSING ENERGY AT TEVATRON

Z_c and W associated production is via

$$p\bar{p} \to q\bar{q}' \to W(\to e/\mu + \nu) + Z_c(\to q\bar{q}), \qquad (3)$$
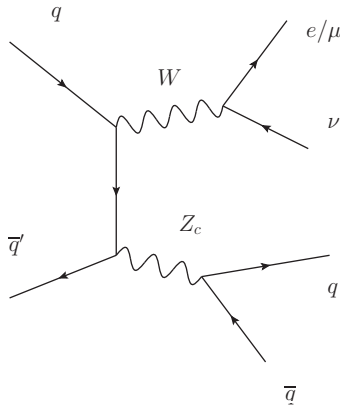
and the Feynman diagram is shown in Fig. 1.

FIG. 1: Feynman diagram for Z_c production at Tevatron.

In order to account for the CDF data, we simulate the di-jet invariant distribution arising from WW/WZ as well as WZ_c production with $m_{Z_c} = 140$ GeV. We choose the benchmark parameter set as $g_V = 0$ and $g_A = 0.2\ g_s$ as discussed above, which do not contradict with other measurements. The di-jet invariant distribution is shown in Fig. 2 after imposing the same cuts with those of [5]. The events are generated by MadGraph [10], then the initial state radiation, final state radiation and fragmentation are carried out by Pythia [11]. The detector response is simulated by PGS. We corrected the jet energy according to Ref. [12]. From the Fig. 2, we can see that the new contribution arising from the extra Z_c can excellently fit the data. Generally speaking, the new contributions from Z_c mainly depends on the magnitude of $g_V - g_A$. For specific choice of *right-handed* coupling, namely $g_V - g_A = 0$, the cross section is zero if parton mass is neglected. Such kind of Z_c signal is not difficult to be examined at current running LHC, similar to the case of deci-weak W'/Z' [6].
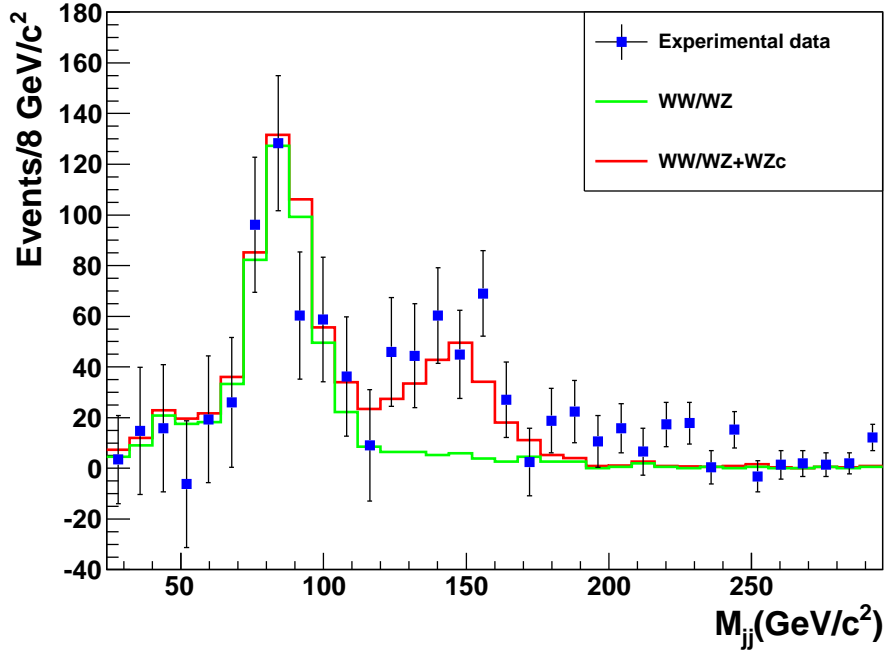
FIG. 2: Di-jet invariant mass distribution at Tevatron with integrated luminosity $\mathscr{L} = 4.3\ fb^{-1}$. Data is taken from Ref. [5].

III. TOP QUARK FORWARD-BACKWARD ASYMMETRY A_{FB}^t AT TEVATRON

Now that we know roughly the coupling among Z_c and quarks, we switch to discuss whether the same parameters can account for top quark forward-backward asymmetry A_{FB}^t at Tevatron. Since the choice of $g_V = 0$ affects $d\sigma/dM_{t\bar{t}}$ insignificantly, we don't show the numerical results here. Instead we will focus on the A_{FB}^t as functions of Δy and $M_{t\bar{t}}$.

The numerical investigation indicated that if we choose $g_A^t = g_A^q$, we can't obtain the observed A_{FB}^t. Instead if we choose

$$g_A^t/g_A^q = 4.5,$$

$A_{FB}^t \simeq 20\%$. For comparison the experimental measurement is $A_{FB}^t \simeq 15.8\% \pm 7.5\%$. In Fig. 3 and 4, we also present A_{FB}^t as functions of Δy and $M_{t\bar{t}}$. From the figures, we can see that data and theory is in agreement within 1σ for Δy distribution while about 1.8σ for $M_{t\bar{t}}$ distribution. It is obvious that the Z_c plus SM contributions can improve the agreement
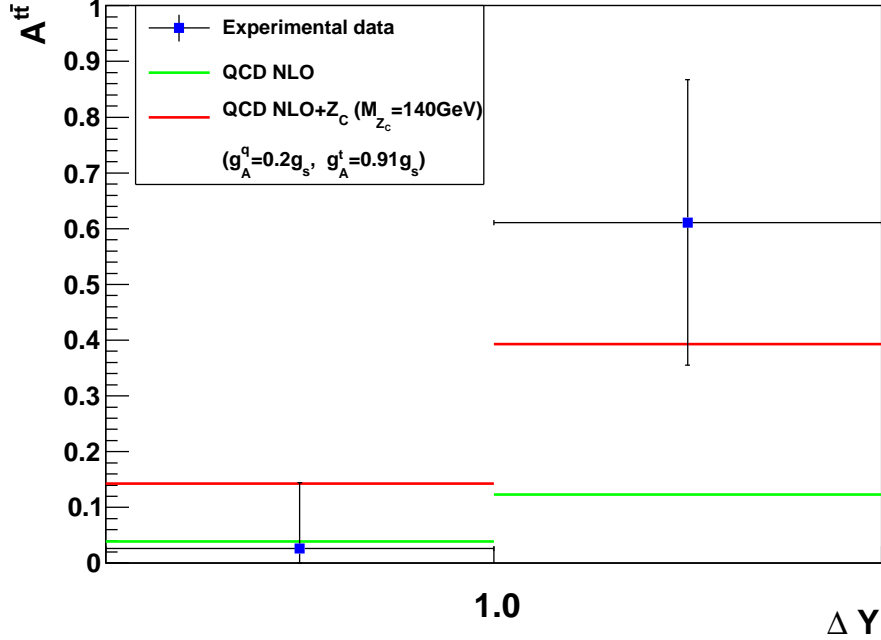
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between theory and data greatly.

FIG. 3: A_{FB} as a function of Δy at Tevatron. Data is taken from Ref. [2].

IV. CONCLUSIONS AND DISCUSSIONS

Motivated by recent measurement of di-jet distribution associated with e/μ and missing energy by CDF, we re-examine the previous idea, namely the new massive color-octet axial-vector-like boson Z_c, to account for A_{FB}^t observation. Our numerical results showed that Z_c can explain the new di-jet bump within allowed parameters. We also investigated whether such Z_c can account for A_{FB}^t. We found that if $g_A^t/g_A^q \simeq 4.5$ the theory and data is in excellent agreement. Moreover the A_{FB}^t distributions as functions of Δy and $M_{t\bar{t}}$ are consistent with data within 1σ and about 1.8σ respectively.

At the LHC, the new Z_c can be easily discovered via the WZ_c associated production. Once Z_c is discovered the detailed properties, such as spin, coupling structure etc., can also be studied in top pair production processes. Here the observables of one-side forward-backward asymmetry [13] and/or edge charge asymmetry [14] can be utilized to analyze the event samples.
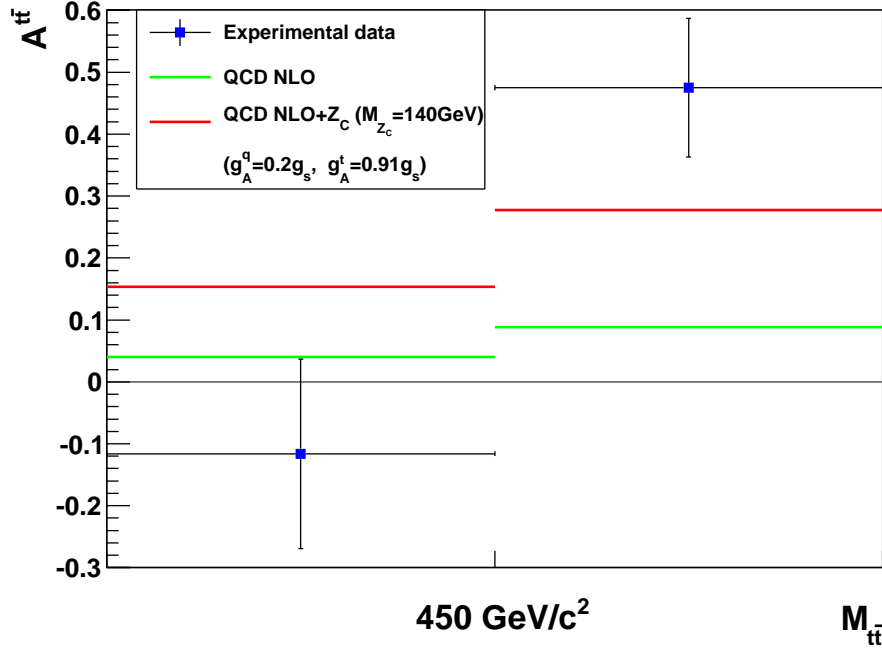
FIG. 4: A_{FB} as a function of $M_{t\bar{t}}$ at Tevatron. Data is taken from Ref. [2].

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